Eight-Channel Microdisk CW Laser Arrays Vertically Coupled to Common Output Bus Waveguides

Seung June Choi, Zhen Peng, Qi Yang, Sang Jun Choi, and P. Daniel Dapkus, *Fellow, IEEE*

***Abstract*—1.6-nm spectrally spaced eight-channel semiconductor microdisk laser arrays are presented, where high-Q disk lasing modes are vertically coupled out through a common bus waveguide. The spectral channel spacing is achieved by varying the disk resonator radii from 10.6 to 10.95 μm. Typical linewidth of 0.25 nm and side-mode suppression ratio of -20 dB are observed under continuous-wave lasing operation near $\lambda = 1.51$ μm. This is the first demonstration of integrated microresonator laser arrays.**

***Index Terms*—Continuous-wave (CW) laser, integrated microresonator laser array, semiconductor microdisk laser.**

I. INTRODUCTION

CIRCULAR microresonator lasers are attractive light sources in photonic integrated circuits (PICs) due to their cleavage-free lasing cavities and excellent wavelength selectivity. The optical modes in microdisk lasers are whispering gallery modes (WGMs) that result from periodic internal reflection of traveling waves. The lasing behavior of WGMs in microdisk lasers has been studied by observing the radiation from the disk sidewalls [1], [2]. When combined with other high-Q passive and active elements connected through a common I/O bus line, microresonator lasers will enable the fabrication of sophisticated PICs that take full advantage of compact chip layouts.

Recently, bus-coupled microdisk lasers have been proposed where high-Q disk lasing modes are either laterally [3] or vertically [4] coupled out through the bus waveguides. Vertically coupled schemes are advantageous since the material compositions and physical separation of the I/O bus and disk resonator waveguides can be independently designed and controlled. In other words, we can realize a compact laser array by connecting multiple microdisk laser elements that are vertically coupled to a low-loss common bus channel waveguide.

In this paper, we present eight-channel continuous-wave (CW) laser arrays using vertically coupled microdisk resonators. The microdisks have slightly different radii and offer 1.6-nm spectral channel spacing that corresponds to the 200-GHz international telecommunications union (ITU) grid spacing in optical wavelength division multiplexing (WDM) protocols. These lasers utilize technologies entirely compatible with the approaches for fabricating tunable filters and switches [5]–[7], which makes it feasible to realize monolithic PICs.

The remainder of this paper is organized as follows. Section II describes the epitaxial wafer structure with the device fabrication flow used in this experiment. Section III contains the measured results and discussions.

II. DEVICE FABRICATION

The epitaxial wafer structure used for the vertically coupled microdisk lasers was grown by metal–organic chemical vapor deposition (MOCVD). It has two vertically stacked waveguides, the I/O bus waveguide and the active quantum well (QW) disk core, respectively, which are separated by a 0.8-μm-thick InP coupling layer. The disk core, with total thickness of 0.4 μm, consists of two separate confinement layers separate confinement heterostructure (SCH) with $\lambda_{\rm SCH} = 1.25$ μm and four QWs (0.5% compressively strained) with emission wavelength at $\lambda_w = 1.51$ μm and three barriers with $\lambda_b = 1.25$ μm. Next, the n-doped coupling layer and n-doped ($\sim 3 \times 10^{17}$ cm^{-3}) I/O bus waveguide layer with $\lambda_{WG} = 1.1$ μm are grown followed by the top n-cladding InP layers.

To initiate the device fabrication, I/O bus waveguides are lithographically defined and dry etched. The entire structure is then flipped over and thermally bonded to another InP transfer wafer. The wafer-bonded sample is polished and the remaining InP from the original substrate is completely removed by selective chemical wet etching solutions. Smooth microdisk mesas with vertical sidewalls are produced on the exposed surface by using CH_4-based chemistry in a reactive ion etching (RIE) discharge [8]. The disk radii (r) vary from 10.6 to 10.95 μm with 0.05-μm difference on average to achieve 1.6-nm spectral spacing for eight channels. After the device surface is planarized by photosensitive polyimide, electrodes are formed on the disks. Cured polyimide patterns serve as self-aligned openings for the metal contacts that afford efficient current injection into the disks along the periphery region. The low heat conductivity (typically, $0.2 \sim 0.4$ W/K $\cdot$ m) of polyimide ensures good thermal insulation between the disks so that biasing one laser does not affect the adjacent laser through heating effects. Details on further processes can be found in [4]–[7]. Fig. 1 shows the schematic cross-sectional view of a unit active microdisk vertically coupled to a bus waveguide. The white block in Fig. 1 is an air gap, approximately 1.2-μm wide, which corresponds to the physical separation between a cylindrical post and bus waveguide underneath the disk resonator. The air gap serves as a low-index sidewall cladding of the bus waveguide that offers lateral confinement. A micrograph showing the top view of the fabricated disk array is given

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The authors are with the Department of Electrical Engineering–Electrophysics, University of Southern California, Los Angeles, CA 90089 USA.

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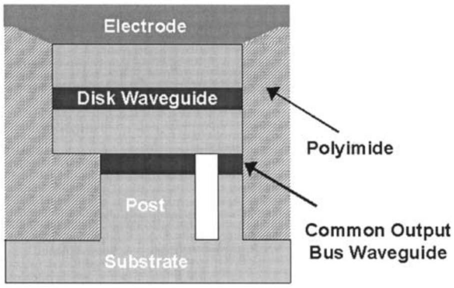

Fig. 1. Schematic cross-sectional view of a bus-coupled microdisk laser.

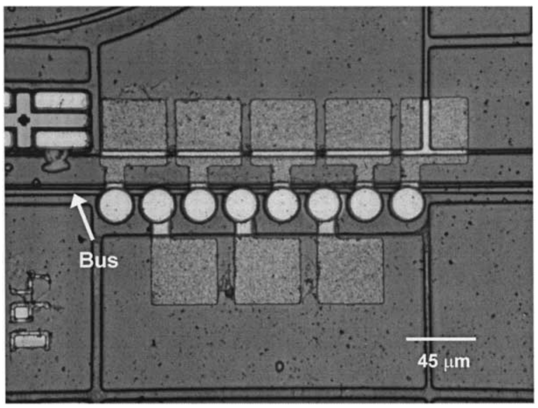

Fig. 2. Micrograph showing the top view of the fabricated eight-channel microdisk array vertically coupled to a single bus waveguide.

in Fig. 2. The eight-channel microdisk lasers are connected through a common high index contrast n-doped output bus waveguide that is 480-μm long. The measured optical losses in the bus waveguides are $3 \sim 5$ cm^{-1} [9].

III. Results and Discussions

Bus-coupled microdisk lasers can be modeled in an approximate manner as Fabry–Perot interferometers where the coupling between the resonators and buses is analogous to mirror losses, i.e., $\kappa_i = 1 - R_i$. κ_i denotes the optical power coupling coefficient between the "ith bus waveguide and the disk resonator. When the residual loss (α_i) and length (L) of the lasing cavity are known, the threshold gain ($g_{\rm th}$) can be expressed as follows:

$$g_{\rm th} = \alpha_i + \frac{1}{L}\ln\left(\frac{1}{R}\right), \qquad \text{where } L = \pi r \text{ and } R = \sqrt{R_1 R_2}. \tag{1}$$

For the given device structures, α_i, r, κ_1, and κ_2 are found to be ~ 5 cm^{-1}, $10.6 \sim 10.95$ μm, $\sim$0.05 and 0 (i.e., the disk is coupled to a single bus line), respectively [4]. The estimated threshold modal gain is $g_{\rm th} \approx 20$ cm^{-1}. It is straightforward to see that $g_{\rm th}$ increases with κ. κ must be maintained at moderate values not to have $g_{\rm th}$ exceed the maximum attainable gain for lasing. Ideally, the resonant wavelength is not affected by the value of κ. However, in actual devices, changes in κ are usually achieved by altering the material and/or geometry of the disk resonators, which affects the modal index and the resultant lasing wavelength as well.

The CW lasing characteristics at room temperature have been measured for eight-channel microdisk arrays. We use a free-

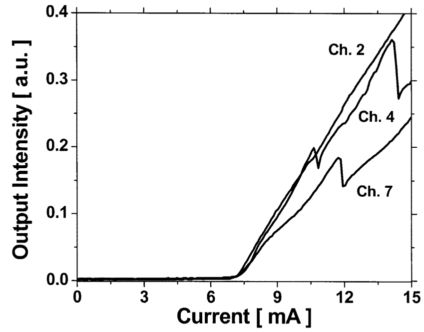

Fig. 3. L–I curves measured from different microdisks corresponding to channels 2, 4, and 7, respectively. Several abrupt "kinks" appear on the L–I characteristics.

space optical lens that is precisely aligned to one of the bus waveguides and collects the output laser coupled through the AR-coated bus facets. The typical L–I curves measured from different microdisks in the array (i.e., different channels) are given in Fig. 3, where low threshold ($\sim$ 7 mA) CW operation is observed. The typical output power measured from a single microdisk laser, which is spectrally integrated by a photodetector, exceeds 20 μW at a pumping range of $I \approx 1.5 \times I_{\rm th}$. The maximum output power is saturated at 40 μW or slightly higher for $I > 2.5 \times I_{\rm th}$. Several abrupt "kinks" appear in the measured L–I characteristics for certain devices, which results from mode hopping. When adjacent disk modes, having different radial distributions or azimuthal mode numbers, are not spectrally remote enough from one another, and if both modes are comparably close to the peak gain spectrum, these modes are readily involved in a competition process to acquire gain that results in lasing mode hopping over a range of currents. To avoid mode oscillation, adjacent modes must be separated by larger free spectral range (FSR), which can be achieved by reducing the disk size. The large FSR results in fewer optical modes in the spectral range of interest, which makes it more probable to have single-mode operation. Improved heat sinks are also essential to stabilize the gain characteristics.

The resonant wavelength of a microdisk laser is determined by the resonant condition $2\pi r n_{\rm eff} = m \times \lambda_{\rm resonant}$ (m is an integer), where $n_{\rm eff}$ is the effective modal index. For the given device geometries, $\Delta r = 0.05$ μm leads to $\Delta\lambda_{\rm resonant} = 7.2 \sim 7.6$ nm for the same azimuthal mode number m in the spectral range of interest. Considering the typical FSR ($\sim$ 9 nm) of the presented resonators, we note that $\lambda_{\rm resonant}(r,\ m) - \lambda_{\rm resonant}(r + \Delta r,\ m - 1) = 1.4 \sim 1.8$ nm. Therefore, by making slight variations in the disk radii ($r \rightarrow r + \Delta r$) and choosing the adjacent mode numbers ($m \rightarrow m - 1$), we can achieve the desired spectral channel spacing of $\sim$ 1.6 nm. As a matter of fact, $\lambda_{\rm resonant}$ is highly sensitive to the physical dimension of resonators and the spectral spacing between channels is often detuned due to probable fabrication errors. Slightly detuned characteristics can be corrected by adjusting the bias.

The lasing spectra are measured in the same manner as the L–I curves, but using a cleaved multimode optical fiber probed to a spectrum analyzer. Fig. 4 shows the lasing spectra measured with a spectral resolution of 0.04 nm at $I = 10$ and 13 mA for channels 2 and 8, respectively. Since the amplified spontaneous emissions in the active region are coupled into the disk

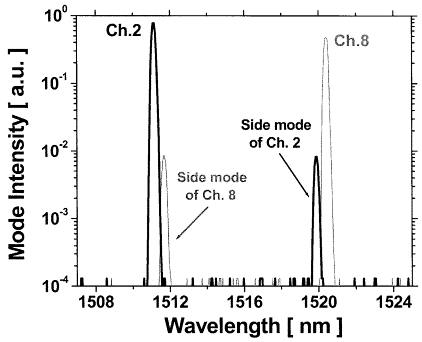

Fig. 4. Lasing spectra measured at $I = 10$ and 13 mA for channels 2 (in bold) and 8, respectively. The mode intensity is plotted in logarithm scales with spectral resolution of 0.04 nm.

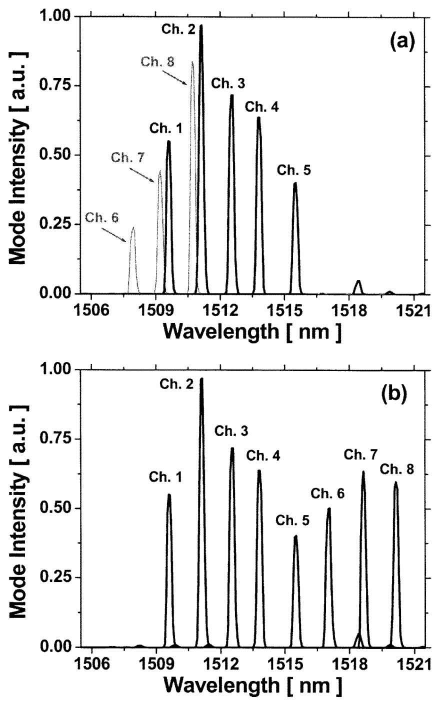

Fig. 5. Superimposed lasing spectra measured from an eight-channel microdisk laser array. (a) The microdisks are equally pumped at $I = 10$ mA. (b) The microdisks for channels 6–8 are pumped at $I = 13$ mA, while the current injection levels for the other disks are maintained at $I = 10$ mA.

WGMs, periodic peaks are observed in the output spectra. The FSR of the given devices is $\sim$ 9 nm, less than the bandwidth containing the entire eight channels (1.6 nm $\times$ 7 $=$ 11.2 nm), which means that certain side modes will exist in between the laser channels. For instance, as shown in Fig. 4, the nearest side mode of channel 2 (1511.1 nm) appears close to the lasing spectrum of channel 8 (1520.4 nm) and vise versa. Those satellite modes may cause detrimental optical crosstalk unless they are distinctly separated from the actual lasing channels. In Fig. 4, we observe that the lasing modes are clearly distinguished by very narrow linewidth of 0.25 nm and the side modes are effectively suppressed with high side-mode suppression ratio (SMSR) of -20 dB.

Fig. 5(a) shows the superimposed lasing spectra measured from eight different microdisks in the laser array, where the microdisks are equally pumped at $I = 10$ mA. The resonant mode nearest to the peak gain spectrum will acquire enough optical gain for lasing in each channel, and the resultant peak intensity contour of the eight-channel lasing spectra resemble the original gain characteristics of the QWs centered at 1510 nm at low currents (over a pumping range $< 1.5 \times$ threshold), as shown in Fig. 5(a). However, at the given current injection level, the lasers wavelengths for channels 6–8 are not achieved at the designed 1.6-nm channel spacing. The lasing modes for those channel can be corrected by red shifting the gain and the spontaneous emission spectra the QWs. Higher injection levels are required to red shift the effective QW band edge by thermal effects. When $I = 13$ mA is applied for channels 6–8, the lasing modes "hop" to the next resonant modes at longer wavelengths and we successfully realize a 1.6-nm spectrally spaced eight-channel laser array, as given in Fig. 5(b). As a matter of fact, we "utilize" the mode-hopping phenomena to obtain the desired channel spacing, which is not actually favorable for ideal laser arrays. This first demonstration of a compact laser array using microresonators suggests the future direction for improved device performances. In ideal designs, the resonant modes of each microdisk must be separated by large FSRs so that each channel has only one optical mode placed within a gain spectral region.

In conclusion, 1.6-nm spectrally spaced eight-channel CW laser arrays are achieved by integrating active microdisk resonators with a single bus waveguide. Typically, a measured linewidth of 0.25 nm and SMSR greater than 20 dB are observed for the microdisks lasing at near $\lambda = 1.51$ μm under CW operation. This is the first demonstration of a compact laser array using microresonators.

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